Resolved nuclear CO(1-0) emission in APM08279+5255: Gravitational lensing by a naked cusp?

Geraint F. Lewis[1], Chris Carilli[2], Padeli Papadopoulos[3,4] & R. J. Ivison[5]

[1] *Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 1710, Australia: Email* gfl@aaoepp.aao.gov.au
[2] *National Radio Astronomy Observatories , PO Box 0, Socorro, New Mexico 87801-0387, USA: Email* ccarilli@nrao.edu
[3] *Astrophysics Division, Space Science Dept. of ESA, ESTEC, Postbus 299, NL-2200 AG, Noordwijk, The Netherlands*
[4] *Sterrewacht Leiden, P.O. Box 9513, 2300 RA Leiden, The Netherlands: Email* ppapadop@astro.estec.esa.nl
[5] *Astronomy Technology Centre, Royal Observatory, Edinburgh, Blackford Hill, Edinburgh, EH9 3HJ, UK: Email* rji@roe.ac.uk

1 February 2008

ABSTRACT

The ultraluminous broad absorption line quasar APM08279+5255 is one of the most luminous systems known. Here, we present an analysis of its nuclear CO(1-0) emission. Its extended distribution suggests that the gravitational lens in this system is highly elliptical, probably a highly inclined disk. The quasar core, however, lies in the vicinity of naked cusp, indicating that APM08279+5255 is truly the only odd-image gravitational lens. This source is the second system for which the gravitational lens can be used to study structure on sub-kpc scales in the molecular gas associated with the AGN host galaxy. The observations and lens model require CO distributed on a scale of ~ 400 pc. Using this scale, we find that the molecular gas mass makes a significant, and perhaps dominant, contribution to the total mass within a couple hundred parsecs of the nucleus of APM08279+5255.

Key words: Ultraluminous Galaxies: Quasars; individual: APM08279+5255

1 INTRODUCTION

Identified serendipitously in a search for high latitude carbon stars, the $z = 3.9$ broad absorption line quasar APM08279+5255 is coincident with an IRAS source with a flux of 0.95Jy at $100\mu m$ (Irwin et al. 1998). Observations with SCUBA reveal that APM08279+5255 possesses a significant submillimetre flux of 75mJy at $850\mu m$ (Lewis et al. 1998), implying a bolometric luminosity of $\sim 5 \times 10^{15} L_\odot$. Imaging reveals that APM08279+5255 is not point-like, but rather is extended over a fraction of an arcsecond with a structure indicative of gravitational lensing (Irwin et al. 1998). The composite nature of APM08279+5255 was confirmed in adaptive optics (AO) images obtained by Ledoux et al. (1998), with the system appearing as a pair of point-like images separated by 0.4 arcsec. Observations with NICMOS on the Hubble Space Telescope (Ibata et al. 1999) and AO images taken with the Keck telescope (Egami et al. 2000) also uncovered a fainter third component between the brighter two. Gravitational lens models derived from these observations suggest that the quasar continuum source has been magnified by ~ 90.

Using IRAM, Downes et al. (1999) detected emission in CO(4-3) and CO(9-8), revealing the presence of warm circumnuclear gas in APM08279+5255. Papadopoulos et al. (2001) were able to search for CO(1-0) and CO(2-1) in this

system using the Very Large Array (VLA). Both were clearly detected associated with the quasar nucleus, as well as a more extended component located several arcsecs from the quasar images. Using locally established values of the CO-to-H_2 ratio, this lone cloud represents $\sim 10^{11} M_\odot$ of cold and/or subthermally excited gas.

In this paper, we present an analysis of nuclear CO(1-0) emission in APM08279+5255 using VLA [1] at high spatial resolution (0.3 arcsec). The CO appears as a partial ring of $\sim$0.6 arcsec diameter. These data suggest a total revision in the gravitational lens model for this source, with the new model involving a 'naked cusp', which naturally accounts for the observed odd-number of images. They also imply that the nuclear CO must be spatially extended on a scale of at least 400 pc, making this the second source in which gravitational lensing can be used as a 'telescope' to explore sub-kpc scale structure of molecular gas in the AGN host galaxy.

---

[1] The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.
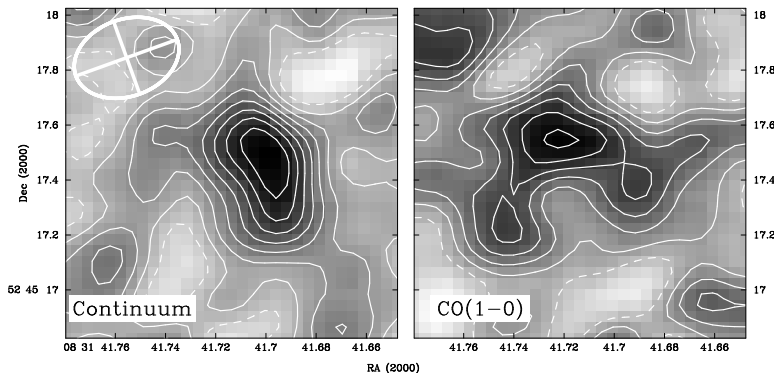
Figure 1. The 23Ghz continuum (left) and CO(1-0) line emission (right) in APM08279+5255. The contours are at -1 (dashed),0,1... $\times \sigma$. The image has been CLEANed and the ellipse in the upper corner of the left-hand panel represents the CLEAN beam. The quasar A image, as determined from NICMOS imaging, lies at 08 31 41.64, 52 45 17.5, offset from the radio emission (Ibata et al. 1999). This is probably due to astrometric errors in the VLA and HST reference frames.

2   OBSERVATIONS AND RESULTS

Observations of the CO(1-0) emission from APM08279+5255 were made in March and April 2001 using the VLA in the B (10 km) configuration. A total of 20 hours were spent on the source. Due to limitations with the VLA correlator, we chose to observe in continuum mode using two 50 MHz bandwidth IFs, each with two polarizations. One IF was centered on the redshifted CO(1-0) line, corresponding to a frequency of 23.465GHz, while the second IF was tuned away from the emission line to a frequency of 23.365GHz. This observing set-up maximizes sensitivity since the effective bandwidth (45 MHz, 575 km/s) closely matches the obseved CO linewidth (Downes et al. 1999), but sacrifices velocity information (Carilli, Menten, & Yun 1999). The source 3C286 was used for absolute gain calibration. The rms noise on the final image is 35μJy beam^{-1} with an effective spatial resolution of FWHM=$0.39'' \times 0.28''$ with a major axis position angle of -70°. Fast switching phase calibration was employed with a calibration duty cycle of 130 seconds (Carilli & Holdaway 1999). The phase stability for all the observations was excellent, such that the array was easily phase coherent over the calibration cycle time. This was demonstrated by imaging the phase calibrator (0824+558) with a similar calibration cycle time, and by imaging the radio continuum emission from APM08279+5255 itself.

The images of the line and continuum emission from APM08279+5255 are shown in Figure 1. The CO line image was generated by subtracting from the visibility data a Clean-Component model of the continuum emission made from the off-line data. The peak surface brightness for the continuum emission is 0.24 ± 0.035 mJy beam^{-1}, with a total flux density 0.41 ± 0.07 mJy. The corresponding numbers for the line emission are 0.183 ± 0.035 mJy beam^{-1} and 0.39 ± 0.09 mJy. The latter corresponds to a velocity-integrated line flux of 0.22 ± 0.05 Jy km/sec, consistent with 0.15 ± 0.045 Jy km/sec deduced for the inner $\sim$ 1arcsec by Papadopoulos et al. (2001)

The continuum emission is extended north-south, with a position angle and spatial extent as expected based on the three component optical gravitational lens. An attempt was made to decompose the continuum map into three point-like images, centred upon the positions derived from the analysis of HST images (Ibata et al. 1999). Given the image resolution, it was not possible to cleanly separate the north-most images (A+C) which have a separation of $\sim$0.15 arcsecs. The relative flux of (A+C)/B$\sim$1.5, quite similar to the optical ratio presented by Ibata et al. (2001). The line emission, on the other hand, shows distinct curvature away from the continuum position angle, and at the 3σ surface brightness level it appears as an almost complete ring with a diameter of about 0.6 arcsec. While the map of the line emission is of low signal to noise, the ring-like structure is apparent in each of several days worth of observations. Also, its size is in agreement with that of the CO(4-3) and CO(9-8) emission (Downes et al. 1999) and the CO(2-1) emission (Papadopoulos et al. 2001). Hence, these observations reveal the gross features of the CO(1-0) emission, although more observations are required to uncover the finer details.

The observed CO(1-0) brightness temperature of the ring (averaged over $\sim$575 km/sec) is 1.4$\pm$0.8 K, which corresponds to an emitted brightness temperature of $T_b \sim$7 K at z$\sim$3.9. A lower limit for the magnification factor of the CO(1-0) emission can be derived assuming the warm gas emitting the high-J CO lines (Downes et al. 1999) to be also emitting the J=1-0. This gas phase is optically thick with $T_{kin} \sim 200K$, in agreement with the inferred dust temperatures (Lewis et al. 1998), which then yields a velocity-averaged filling factor of $f \sim 7/200 = 0.035$. Since differential lensing will "boost" a compact warm region at the expense of a more extended and possibly sub-thermally excited gas phase that emits the CO J=1-0, the true value of f will be larger.

3   GRAVITATIONAL LENSING

The lensing galaxy has yet to be identified in APM08279+5255. Hence, only the quasar positions and magnitudes are available to constrain any lensing model. Other than APM08279+5255, all other lens systems possess an even-number of images. Theoretically, any non-singular mass distribution should produce an odd number of lensed images (Burke 1981), and the ubiquity of even numbers of images has been used to limit the

core radius in lensing systems, as small cores result in the demagnification of one of the images. Due to the brightness of the central source, however, models for APM08279+5255 have required the opposite, a very circular model with a large core / shallow cusp (Lewis et al. 1999; Egami et al. 2000; Munoz et al. 2001). We further explore the lens model of APM08279+5255 in light of the observations presented here.

The concordance between the optical images of APM08279+5255 and the radio continuum at 3.6cm (Ibata et al. 1999) and 23GHz demonstrates they come from coincident regions with a similar scale size. Associated with the active core of APM08279+5255, these regions are smaller than the gravitational lensing caustics. The quite different morphology displayed in the CO image, however, indicates that this emission arises in a larger region, distinct from the continuum radiation. With its extended nature, the CO emitting region can lie under different parts of the caustic network. The CO source, however, can not be significantly more extended than the caustic network, as the resulting image would not show the ring structure seen in Figure 1. Therefore, for a given model, the size of the ring image provides a probe of the scale size of the emitting region.

To form ring-like images, the source must be extended and cover a substantial fraction of the inner caustic structure of the lens; the resulting image is appears as a ring, following the outer critical line in the image plane (see Kochanek, Keeton & McLeod 2001). Examining the critical line structure in all previously published models for APM08279+5255 (Ibata et al. 1999; Egami et al. 2000; Munoz et al 2001), the resulting structure for the Einstein ring of a source centred upon the quasar nucleus should be quite circular, with a radius of ~ 0.2 arcsecs, passing through the two brighter quasar images; such images for extended source can be seen in the models of Egami et al. (2000). This is quite different to the CO structure displayed in Figure 1, with the CO emission clearly showing a roughly east-west extension, with the hole in the ring occurring ~ 0.5 arcsecs from image A. Using the model derived from the HST data (Ibata et al. 1999), we explored the image configurations a range of sizes and shapes, centred upon the quasar source, for the CO emitting region. None reproduced the observed image structure and we reject this previous model.

Naked cusps occur in highly elliptical systems, such as flattened disks, when the inner diamond caustic extends outside the elliptical caustic. A source inside this extension produces three roughly colinear images of similar brightness (Maller, Flores & Primack 1997; Bartelmann & Loeb 1998; Keeton & Kochanek 1998; Moller & Blain 1998; Blain, Moller & Maller 1999; Bartelmann 2000). While gravitational lensing by spiral galaxies has been observed (e.g. B 1600+434; Koopmans, Bruyn & Jackson 1998) no observed lensed quasar system has so far been associated with a naked cusp.

To examine the possibility that the observed image configuration is due to gravitational lensing by a naked cusp, we constructed a simple mass model. Following Batelmann and Loeb (1998), this consists of a truncated flattened disk in a spherical halo. APM08279+5255 has brightened considerably since its discovery (Lewis, Robb & Ibata 1999; E. Ofek priv. comm., see `http://wise-obs.tau.ac.il/~eran/LM`), potentially due to the effects of gravitational microlensing.

Comparing the images obtained in 1998 (Ibata et al. 1999; Egami et al. 2000) and those obtained in 1999 (Munoz et al. 2001), the relative image brightness have changed appreciably, with image B changing from being 78% of image A to only 50% in the latter epoch; such behaviour is extremely suggestive of the action of gravitational microlensing, although longer term monitoring is required to confirm this. Hence, the relative image brightnesses cannot be used to constrain any mass model. Given the sparsity of constraints, we choose to find a model that can recover the image positions, while providing a reasonable description of the observed CO emission. As can be imagined, the parameter space is large, so a range of models that reproduced the quasar positions were chosen and then modeling of the CO emission was undertaken by-eye. With this, therefore, we do not claim that the model presented here is unique, only consistent with the general form of data.

In our chosen model, the disk is highly inclined, presenting a projected axis ratio of 0.25, and the disk truncated at $8h^{-1}$kpc ^{2}, and possess a core radius of $0.065h^{-1}$kpc. The rotation velocity of the disk is 200kms^{-1}. Figure 2 presents the source and image plane for this model, with the elliptical and diamond caustic, and corresponding critical lines apparent. In this model, the quasar images are not substantial magnified, with a total magnification of ~ 7, with the intrinsic source of APM08279+5255 being correspondingly luminous, $L_{bol} \sim 7 \times 10^{14} L_{\odot}$. While extreme, this value is not necessarily outrageous as the unlensed quasar HD1946+7658 possess an intrinsic luminosity of $\sim 4 \times 10^{14} L_{\odot}$ (Hagan et al. 1992), and APM08279+5255 may be a member of this very luminous class of quasars. It must be conceded, however, that the non-uniqueness of the lens model translates into uncertainty in the model magnification and a true determination of the intrinsic properties of APM08279+5255 require models derived from better observational constraints.

The CO source is taken to be have an circular surface brightness distribution centred upon the quasar position. One important aspect of the results presented herein is that APM08279+5255 becomes the second system for which the gravitational lens can be used to study structure on sub-kpc scales in the molecular gas associated with the AGN host galaxy, the first system being the Clover Leaf quasar, H1413+117 (Yun et al. 1998; Kneib, Alloin, & Pello, R. 1998). For APM08279+5255, the observations and lens model require the CO to be distributed on a scale covering a substantial fraction of the caustics in the image plane, but not too large to lose the ring structure. The lower limit to the CO source size based on the modeling is $\sim 400h^{-1}$ pc, while a rough upper limit is ~ 1 kpc. With this model, the CO(1-0) has been magnified by a factor of $\sim 2.5 - 3$. Like the Clover Leaf, we find that the spatial extent and mass of the molecular gas in APM08279+5255 are comparable to those seen in nearby nuclear starburst galaxies (Sanders and Mirabel 1996; Downes and Solomon 1998).

Downes et al. (1999) determined a CO source size of $\sim (80 - 135)h^{-1}$pc for the estimated magnification factors of $\sim 20-7$. This size is much smaller than the one calculated above, while their magnification factors are larger. Their analysis is based upon modeling of CO emission in the grav-

---

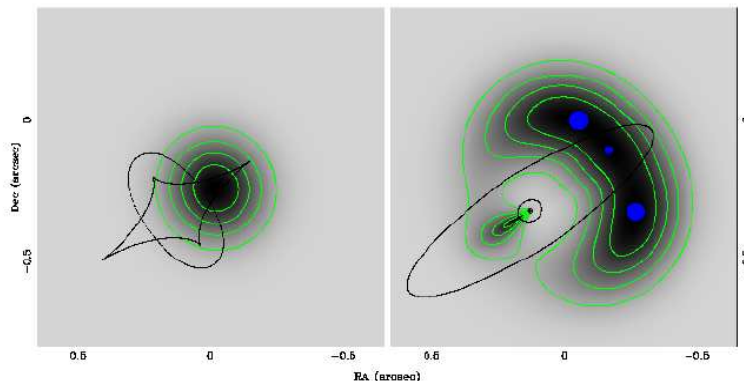^{2} $\Omega = 1$ and $\Lambda = 0$ is assumed throughout

Figure 2. The source plane (left) and image plane (right) for the gravitational lens model for APM08279+5255. The diamond and elliptical caustics, and their corresponding critical lines, are apparent in the panels. The contour lines represent the CO source and image and the filled circles represent the positions and brightnesses of the quasar images as determined from the HST images (Ibata et al. 2000). Note, however, the model presented in the paper results in brightness ratios of $C \sim B \sim 0.75A$, whereas the observed ratios are $C \sim 0.2A$ and $B \sim 0.8A$.

itationally lensed ultraluminous galaxy IRAS F10214+4724 (Downes, Solomon & Radford 1995), whose image is clearly an extended arc-like feature which possesses an essentially linear magnification. Such a simple model is probably a poor representation of the lensing in APM08279+5255. Additionally, Downes et al. (1999) assumed that the velocity filling factor is unity, substantially larger than the value derived in Section 2; as the intrinsic source radius in their model scales inversely with this value and the magnification factor is proportional to it. For f$\sim$0.35, a value well within our estimated range, the Downes et al. (1999) model yields an upper limit for the intrinsic source size and a lower limit for the magnification factor that our similar to ours.

Accounting for the influence of gravitational lensing, the velocity-integrated CO(1-0) flux density implies that the nuclear content of molecular gas in APM08279+5255 is $\sim 10^{10}h^{-2}M_{\odot}$, assuming a CO-to-$H_2$ conversion factor of $\sim 1(M_{\odot}$ km sec^{-1} pc$^2)^{-1}$ which is typical for starburst/kinematically violent, UV-intense environments of gas-rich, IR-ultraluminous systems (Downes & Solomon 1998). Assuming the CO is in a rotating disk, the dynamical mass can be calculated from the radius of ~ 500 pc set by the lens modeling, and using a rotational velocity of 350 km sec^{-1} set by the observed of line velocity HWHM = 250 km sec^{-1} and assuming a disk inclination angle of 45° (Downes et al. 1999). The implied dynamical mass is 1.5×10^{10} M$_{\odot}$ within $\sim$500 pc of the nucleus, consistent with the value derived from the CO flux. Hence it appears likely that the molecular gas mass makes a significant, and perhaps dominant, contribution to the total mass within a few hundred parsecs of the nucleus in APM08279+5255, unless the nuclear CO disk is close to face-on. A similar conclusion has been reached for most nearby nuclear starburst galaxies (Downes and Solomon 1998).

4   CONCLUSIONS

This paper has presented resolved images of nuclear CO(1-0) emission in the gravitationally lensed BAL quasar APM08279+5255. While the continuum emission is found to

be well aligned with the optical quasar images, the CO(1-0) is more extended, with a broken ring-like appearance. Such a structure is consistent with the action of gravitational lensing, with the continuum emission occurring on the scale of the quasar core, while the CO(1-0) arises from a larger region and is differentially magnified. The three-image nature of APM08279+5255 has posed a problem for lens modeling, as an extremely large, flat core is required to produce the central image. Such three image configurations are a nature consequence of gravitational lensing by a flattened potential which can produce naked cusps. Modeling of the CO(1-0) emission supports this hypothesis, although a deficit in constraints implies that the model is not unique. An immediate prediction of this model is that the lensing galaxy, whose position could be revealed by observing below the Lyman limit for this system ($\lesssim$ 4400Å), hence removing the glare from the quasars, should be offset $\sim$ 0.5arcsec from the quasar image, rather than lying behind the quasar images.

Currently, our CO images of APM08279+5255 are of limited signal-to-noise. However, with further integration a detailed map of the CO image can be made. As this region will be free from the effects of microlensing, and as its extended nature provides many more constraints (Kochanek, Keeton & McLoed 2001), such imaging has the potential to provide a more accurate model of the lensing in APM08279+5255 than from the quasar images.

REFERENCES

Alloin D., Guilloteau S., Barvainis R., Antonucci R., Tacconi L., 1997, A&A, 321, 24
Bartelmann M., 2000, A&A, 357, 51
Bartelmann M., Loeb A., 1998, ApJ, 503, 48
Barvainis R., Maloney P., Antonucci R., Alloin D., 1997, ApJ, 484, 695
Blain A. W., Moller O., Maller A. H., 1999, MNRAS, 303, 423
Burke W. L., 1981, ApJ, 244, L1
Carilli, C.L., Menten, K.M., and Yun, M.S. 1999, APJ, 521, L25
Carilli, C.L. and Holdaway, M.A. 1999, Radio Science, 34, 817
Downes D., Neri R., Wiklind T., Wilner D. J., Shaver P. A., 1999, ApJ, 513, L1

Downes, D. & Solomon, P.M. 1998, APJ, 507, 615

Downes D., Solomon P. M., Radford S. J. E., 1995, ApJ, 453, L65

Egami E., Neugebauer G., Soifer B. T., Matthews K., Ressler M., Becklin E. E., Murphy T. W., Dale D. A., 2000, ApJ, 535, 561

Hagen, H.-J. et al. 1992, A&A, 253, L5

Ibata R. A., Lewis G. F., Irwin M. J., Lehár J., Totten E. J., 1999, AJ, 118, 1922

Irwin M. J., Ibata R. A., Lewis G. F., Totten E. J., 1998, ApJ, 505, 529

Keeton C. R., Kochanek C. S., 1998, ApJ, 495, 157

Kneib, J.-P., Alloin, D., & Pello, R. 1998, A&A, 339, L65

Kneib J. -., Alloin D., Mellier Y., Guilloteau S., Barvainis R., Antonucci R., 1998, A&A, 329, 827

Kochanek C. S., Keeton C. R., McLeod B. A., 2001, ApJ, 547, 50

Koopmans L. V. E., de Bruyn A. G., Jackson N., 1998, MNRAS, 295, 534

Ledoux C., Theodore B., Petitjean P., Bremer M. N., Lewis G. F., Ibata R. A., Irwin M. J., Totten E. J., 1998, A&A, 339, L77

Lewis G. F., Chapman S. C., Ibata R. A., Irwin M. J., Totten E. J., 1998, ApJ, 505, L1

Lewis G. F., Robb R. M., Ibata R. A., 1999, PASP, 111, 1503

Maller A. H., Flores R. A., Primack J. R., 1997, APJ, 486, 681

Moller O., Blain A. W., 1998, MNRAS, 299, 845

Munoz, J. A., Kochanek, C. S., Keeton, C. R., 2001, ApJ, 558, 657

Papadopoulos P., Ivison R., Carilli C., Lewis G., 2001, Nature, 409, 58

Sanders D. B., Mirabel I. F., 1996, ARA&A, 34, 749

Yun, M.S., Scoville, N.Z., Carrasco, J.J., & Blandford, R.D. 1997, APJ, 479, L9